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Analysis of Seismic Data Collected Near the Eastern Kazakh and Nevada Test Site

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Seismographic stations were operated for several months during 1987 at three sites within 250 km of the Kazakh Test Site (KTS) in the USSR and through most of 1988 and early 1989 at three sites within 250 km of the Nevada Test Site (NTS) in the US. The three Soviet sites included Karkaralinsk (KKL), Bayanaul (BAY), and Karasu (KSU), and the three US stations were located at Nelson, NV (NEL), Deep Springs, CA (DSP), and Troy Canyon, NV (TRC). All six stations were equipped with high-frequency, three-component surface (1-80 Hz) and borehole (.2-80 Hz) instruments.

We have analyzed nearly 2,000 recordings of ambient ground noise collected at the US stations and have systematically reexamined several hundred noise measurements from the USSR sites in order to compare surface and borehole noise levels among the six locations. Wind speed was recorded during most of the deployment at each site, making possible a comparison of the noise levels at each station of a function of wind speed. The operational periods yielded data covering a reasonable sampling of meteorological conditions, although

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19. the overall duration of occupation of each site was too short to permit a reliable characterization of seasonal noise variations.

We concluded that:

1. In general, noise levels in the boreholes were affected by wind conditions to a much smaller degree than were the surface emplacements.
2. Wind did not become a noticeable source of noise at the surface emplacements until a minimum wind speed was reached (typically 4 to 5 m/sec).
3. At frequencies between 3 and 10 Hz, surface and borehole noise levels were comparable. However, downhole noise levels at higher frequencies were greatly reduced.
4. In the 3-10 Hz band, surface and borehole emplacements in the western US were generally quieter than those in Kazakhstan.
5. In the 10-80 Hz band, surface installations in the western US were considerably noisier than surface installations in Kazakhstan, but borehole installations in both regions yielded comparable noise levels. We suspect that the difference in surface vault quality between the two sets of stations is a significant factor. In this frequency band the borehole noise levels were lower than the surface at all stations.

Summary

Seismographic stations were operated for several months during 1987 at three sites within 250 km of the Kazakh Test Site (KTS) in the U.S.S.R. and through most of 1988 and early 1989 at three sites within 250 km of the Nevada test site (NTS) in the U.S. The three Soviet sites included Karkaralinsk (KKL), Bayanaul (BAY), and Karasu (KSU), and the three U.S. stations were located at Nelson, NV (NEL), Deep Springs, CA (DSP), and Troy Canyon, NV (TRC). All six stations were equipped with high-frequency, three component surface (1-80 Hz) and borehole (.2-80 Hz) instruments.

We have analyzed nearly 2,000 recordings of ambient ground noise collected at the U.S. stations and have systematically reexamined several hundred noise measurements from the U.S.S.R. sites in order to compare surface and borehole noise levels among the six locations. Wind speed was recorded during most of the deployment at each site, making possible a comparison of the noise levels at each station as a function of wind speed. The operational periods yielded data covering a reasonable sampling of meteorological conditions, although the overall duration of occupation of each site was too short to permit a reliable characterization of seasonal noise variations.

We conclude that:

1. In general, noise levels in the boreholes were affected by wind conditions to a much smaller degree than were the surface emplacements.

2. Wind did not become a noticeable source of noise at the surface emplacements until a minimum wind speed was reached (typically 4 to 5 m/sec).

3. At frequencies between 3 and 10 Hz, surface and borehole noise levels were comparable. However, downhole noise levels at higher frequencies were greatly reduced.

4. In the 3-10 Hz band, surface and borehole emplacements in the western U.S. were generally quieter than those in Kazakhstan.

5. In the 10-80 Hz band, surface installations in the western U.S. were considerably noisier than surface installations in Kazakhstan, but borehole installations in both regions yielded comparable noise levels. We suspect that the difference in surface vault quality between the two sets of stations is a significant factor. In this frequency band the borehole noise levels were lower than the surface at all stations.

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ANALYSIS OF HIGH FREQUENCY SEISMIC NOISE IN THE WESTERN U.S. AND EASTERN KAZAKHSTAN

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1. Introduction

Seismographic stations were operated for several months during 1987 at three sites within 250 km of the Kazakh Test Site (KTS) in the U.S.S.R. (Berger *et al.*, 1988) and through most of 1988 and early 1989 at three sites within 250 km of the Nevada test site (NTS) in the U.S. The three Soviet sites -Karkaralinsk (KKL), Bayanaul (BAY), and Karasu (KSU)- are shown in Figure 1 and the locations of the three U.S. stations -Nelson (NEL), Deep Springs (DSP), and Troy Canyon (TRC)- are given in Table 1 and depicted in Figure 2. All six stations were equipped with high-frequency, three component surface (1-80 Hz) and 100 m deep borehole (.2-80 Hz) instruments. The U.S. stations were also equipped with broad band seismometers (.0027 to 10 Hz), but data from these instruments are outside the frequency range of interest to this study and will not be discussed.

Table 1: Locations of the western U.S. stations used in this study.

Station Name	Latitude	Longitude	Elevation
Nelson (NEL)	35° 39.02" N	114° 50.65" W	1326 m
Deep Springs (DSP)	37° 22.17" N	117° 58.45" W	1692 m
Troy Canyon (TRC)	38° 20.98" N	115° 35.11" W	1815 m

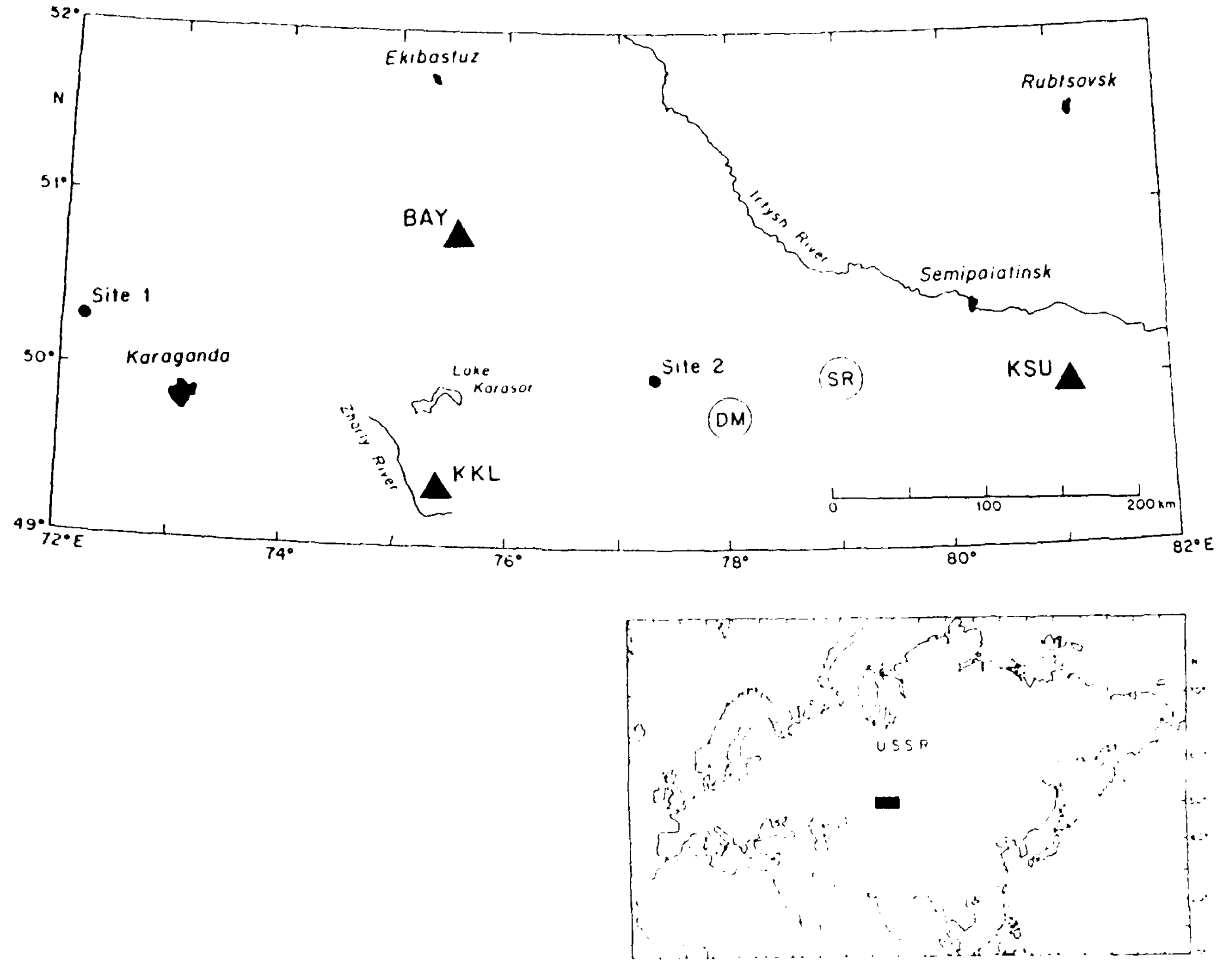

Figure 1. Locations of the U.S.S.R. seismic stations at Karkaralinsk (KKL), Bayanaul (BAY) and Karasu (KSU). The circled DM and SR indicate the locations of the Soviet nuclear test sites at Degelen Mountain and Shagan River, respectively.

Figure 2. Locations of the U.S. seismic stations at Deep Springs (DSP), Nelson (NEL), and Troy Canyon (TRC). The Nevada nuclear test site is outlined and labeled NTS.

We have analyzed nearly 2,000 recordings of ambient ground noise collected at the U.S. stations and have systematically reexamined several hundred noise measurements from the U.S.S.R. sites in order to compare surface and borehole noise levels among the six locations. Wind speed was recorded during most of the deployment at each site, making possible a comparison of the noise levels at each station as a function of wind speed. Noise samples were generally taken at the same time each day, so that our data set does not permit a study of diurnal variation of noise levels. The operational periods yielded data covering a reasonable sampling of meteorological conditions, although the overall duration of occupation of each site was too short to permit a reliable characterization of seasonal noise variations. Before discussing these data, we will give a brief description of the geologic setting and seismic equipment.

2. Station description

Berger et al. (1988) gave a detailed description of the U.S.S.R. equipment and sites; therefore we shall focus on the U.S. seismographic sites and equipment and recall briefly the characteristics of the Soviet stations for comparison.

2.1. Station Setting

The three U.S. stations were located in the tectonically active Basin and Range Province of the western U.S. At each site the seismic vaults were built on granitic intrusions outcropping near the base of mountain ranges (Table 2). Earthquakes in the Basin and Range are generally shallow (<15 km) and fault plane solutions reflect the extensional tectonics of the region (e.g. Smith and Sbar, 1974). The heat flow is high and the upper mantle velocity is relatively low —7.8 to 7.9 km/sec (Stewart, 1978; Priestley *et al.*, 1982)—. The crust beneath southern Nevada is 25 to 30 km thick (Davis, 1980) and the region is generally in isostatic equilibrium at crustal depths (Stewart, 1978).

Table 2.: Rock type and reference for the western U.S. stations used in this study.

Station	Rock Type	Age	Reference
NEL	Medium-grained quartz monzonite to granite	35 My (Pb-Pb), 27 My (K-Ar)	Longwell (1963)
DSP	Granodiorite, variable texture	170 ± 5 My (K-Ar)	McKee (1968)
TRC	Medium-grained quartz monzonite	Mesozoic	Cebull (1970)

In contrast Eastern Kazakhstan is largely aseismic, with a thick crust (about 50 km), low heat flow and high P_n velocity (8.3 to 8.5 km/sec at Karkaralinsk and Bayanaul, and 8.0 to 8.2 km/sec at Karasu, Leith, 1987). Studies have concluded that both the Curie isotherm and the isostatic compensation depth extend into the mantle (Belyaevsky et al., 1981).

All three Soviet stations were located in late Paleozoic to early Mesozoic granitic intrusions thought to be similar to the Degelen test site intrusives. Although they extend as much as a hundred square miles at the surface, seismic investigations conducted near Karkaralinsk indicate that such intrusions are mushroom-shaped and narrow with depth (Leith, 1987). Gravity studies near Karasu found that the granitic intrusion has a lower density than the surrounding highly deformed Paleozoic sedimentary and metamorphic rock (Leith, 1987).

Significant differences between the regions sampled in this study were observed during large chemical explosion experiments in the U.S.S.R. and U.S. in 1987 and 1988 respectively (Given *et al.*, 1989). At comparable epicentral distances and for the same explosion yields, signals recorded in the Soviet Union were very strong, while the signals recorded at the U.S. stations barely exceeded the noise level. This is thought to reflect higher seismic attenuation in the crust and upper mantle in the western U.S. than in Kazakhstan.

2.2. Vault Construction

The vaults at U.S. stations were small cement buildings constructed on granitic bed rock. A small excavation, no more than a meter deep, was blasted in the rock and the site was scraped clean in preparation for vault construction. A 100 m well for the borehole instruments was then drilled within the boundaries of the vault, and cased prior to pouring the cement floor. Surface seismometers were placed directly on the vault floor, and the broad-band instruments were installed in a shallow 10 m borehole drilled just outside the vault. After the vault was constructed, the structure was covered with a dirt mound to reduce its wind profile.

The vaults in the U.S.S.R. were also dug in granite, but with a greater excavation. They were completely buried and so had a very low wind profile. As in the case of the U.S. installations, the wellhead for the borehole instruments was located within the vault, but surface seismometers were installed on a large cement pier decoupled from the vault floor.

2.3. *Seismographic Equipment and Recording System*

As illustrated on Figure 3, three types of three component sensors were deployed at each U.S. site. Teledyne Geotech 54100 borehole units, each housing three S750 accelerometers, were installed in the approximately 100 m deep boreholes. These instruments have a response that is flat to acceleration in a 0.2-90 Hz passband. (In contrast, the U.S.S.R. borehole instruments had been modified to have a flat velocity response). The surface instruments in both countries were Teledyne Geotech GS-13 velocity sensors. In addition, CMG3 extended broadband sensors, manufactured by Guralp Systems, were deployed at U.S. sites in shallow 10 m boreholes. These instruments have a response flat to ground velocity from .0027 to 10 Hz. In order to take advantage of the full dynamic range of the system, all borehole and surface channels were recorded at both low and high gain. Including the CMG3 seismometers, this resulted in 15 channels of data per site. Broad-band data were not collected at the Soviet sites and will not be discussed in this study.

The borehole and surface channels were sampled at 250 s.p.s using a Refraction Technology (RT-97) 16-bit data acquisition system. The CMG3 channels were digitized at 125 s.p.s. The RT-97 also provided 6-pole, low-pass anti-aliasing filters at 80 and 40 Hz respectively, and adjustable amplification. Timing was provided by a GOES clock, with the RT-97 internal clock as back-up.

2.4. *Detection and Recording System*

The data were transmitted digitally by underground cable (Deep Springs) or microwave link (Nelson and Troy Canyon) to an Earth station, and from there to the Scripps Institution of Oceanography *via* 56 Kbps satellite links (Figure 3). A Refraction Technology interface unit (RT-44C) then collected all 45 channels of data —15 per site— into 0.5-second buffers which were processed on a microVax workstation. The STA/LTA detection software used in this study was originally developed by the U.S.G.S. for the ANZA network (Berger et al., 1984; and Berger et al., 1988). For each detection, 50 seconds of pre-trigger and 20 seconds of post-trigger memory were recorded on 9-track tape. The system was also used in a preset-time mode to record noise. The same detection algorithms were used in the U.S. and the U.S.S.R.; however, separate data loggers were used independently at each site in the U.S.S.R., whereas in the telemetered U.S. system, only events detected at two or more stations were recorded.

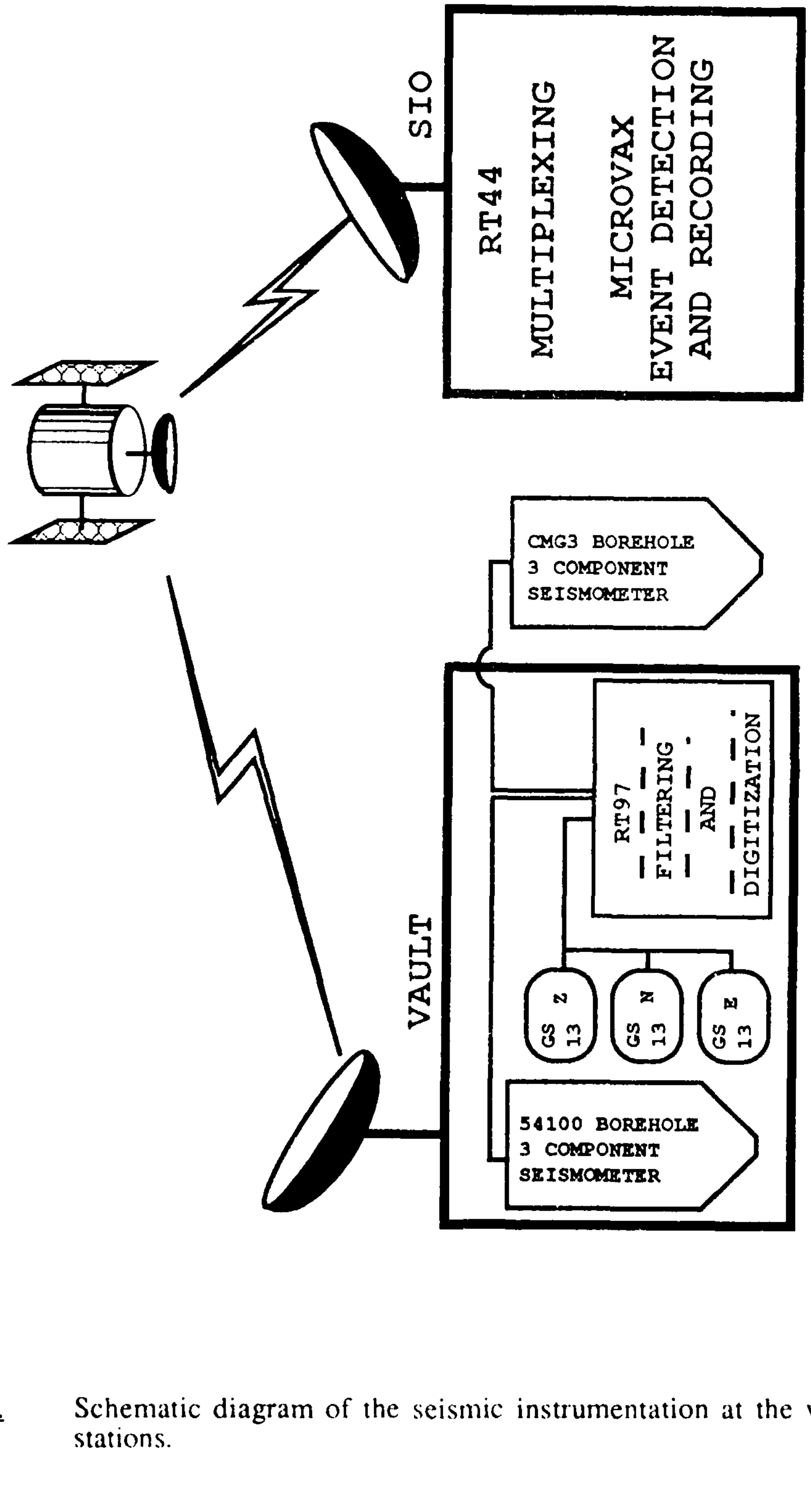

Figure 3. Schematic diagram of the seismic instrumentation at the western U.S. stations.

2.5. System Responses

Figure 4 shows the system response for the borehole and surface systems in the U.S. and U.S.S.R. These curves include the seismometer transfer functions, the anti-aliasing filter, and gain factors for the analog to digital converter. At the high end of the pass-band, all responses are shaped by the low-pass anti-aliasing filter. The seismometer controlled the low-frequency shape of the response curve, with the following corners:

- For all surface vault systems (velocity sensors): 1 Hz.
- For all U.S.S.R. borehole systems (velocity sensors): 0.2 Hz
- For U.S. borehole systems (acceleration sensors): 2 Hz prior to June, 1988, and 0.2 Hz after June, 1988.

2.6. System Noise Performance

To determine the overall system noise performance for the U.S. stations, we performed identical experiments to those reported in Berger *et al.* (1988) for the U.S.S.R. deployment. These included clamping the seismometer mass (for surface seismometers only) and replacing the seismometer by an equivalent output impedance. The noise spectrum of the clamp test was dominated by digitizer noise and was therefore not used.

Figure 5 summarizes representative results of these system tests. Curve A is a power spectrum depicting low noise conditions at Deep Springs with the amplifier gain set at 48 dB. Curves B and C are the system noise tests, corrected for the surface and borehole system responses respectively, with the seismometer replaced by an equivalent resistance, recorded at 48 dB. Curve D is the theoretical noise level of the borehole seismometers as supplied by the manufacturer, which does not include noise generated in the amplifiers and filters (Berger *et al.* 1988). Curve A merges with curve B at 80 Hz. As a result, ground noise is masked by system noise above these frequencies. When the amplifier gain was set below 48 dB, the ground noise in some cases was masked by system noise at a lower frequency (e.g. 40 Hz).

Comparison of curves C and D leads to the conclusion that the internal noise of the borehole seismometer was well above the digitizer noise at all frequencies. Thus for the borehole channels, the seismometer noise (curve D) determines the level of the smallest ground motion detectable. However in the analysis of surface data recorded at gains lower than 48 dB, we had to be careful to distinguish between digitizer noise and ground noise.

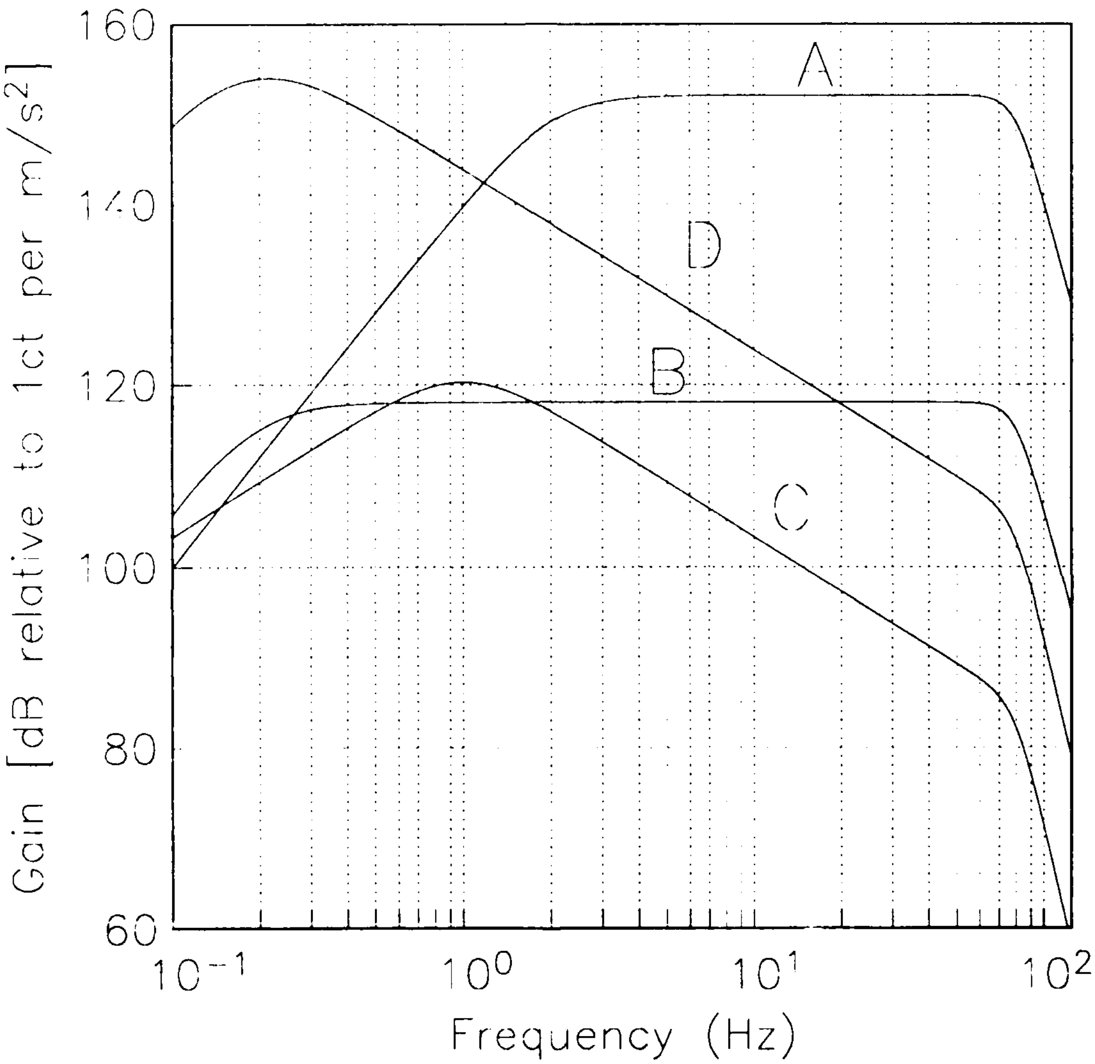

Figure 4. System responses (corrected to acceleration). A and B are the responses of the U.S. borehole systems before and after June 1988 (respectively). C is the response of the U.S. and U.S.S.R. surface systems. D is the response of the U.S.S.R. borehole system.

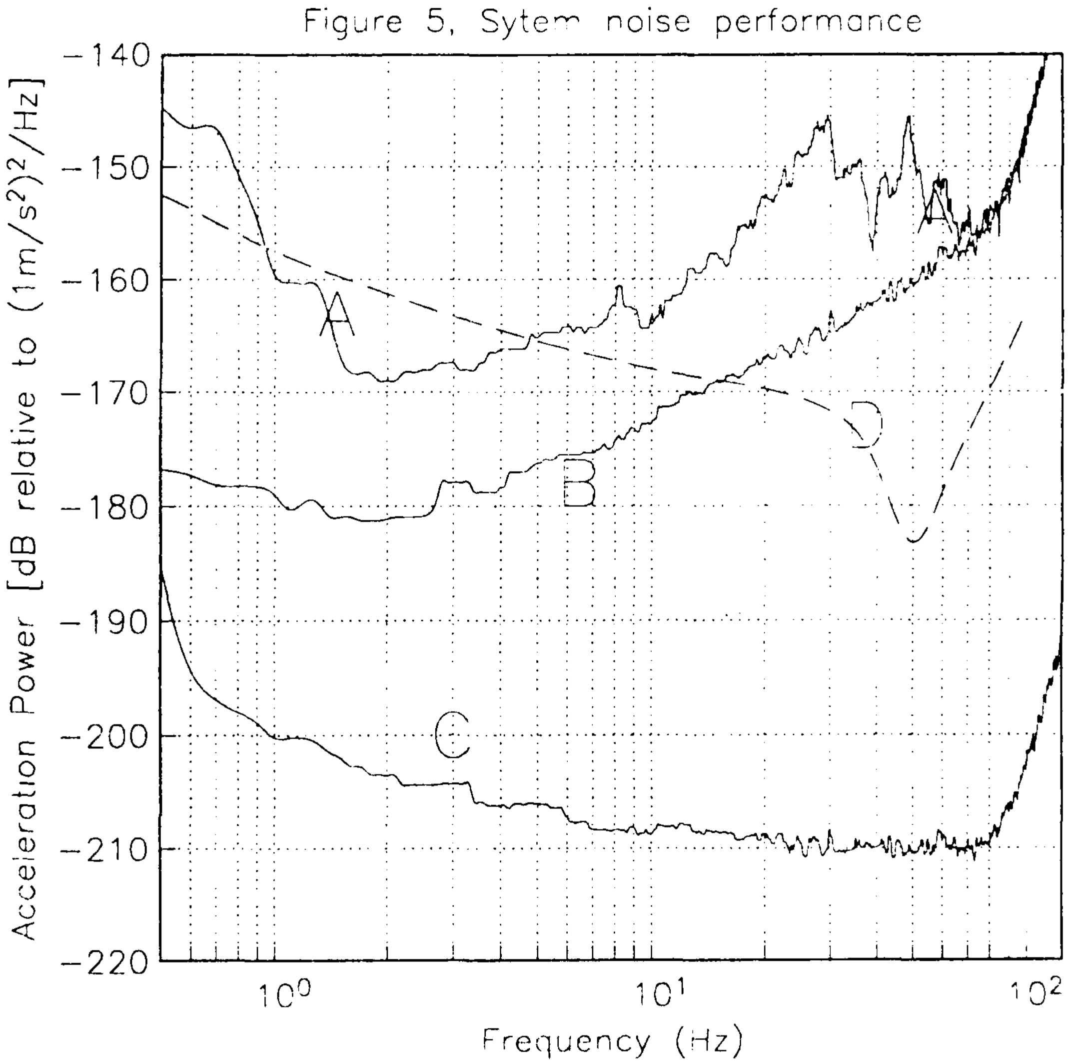

Figure 5. Summary of system noise performance. Curve A is a power spectrum depicting low noise conditions at Deep Springs with the amplifier gain set at 48 dB. Curves B and C are the system noise tests, corrected for the surface and borehole system responses respectively, with the seismometer replaced by an equivalent resistance, and recorded at 48 dB. Curve D is the theoretical noise level of the borehole seismometers as supplied by the manufacturer, which does not include noise generated in the amplifiers and filters (Berger *et al.* 1988).

3. Methodology

3.1. Data Description

Noise recordings were nominally taken at each station once a day, with occasional gaps of several days. As a result we have sampled a variety of meteorological conditions (particularly wind speed) over the span of deployment. During May, 1988, the noise level at Troy Canyon was consistently much higher, at all wind speeds, than during other months. We attributed this anomaly to spring run-off in a nearby stream and omitted these data in our analysis. Figure 6 shows the number of available noise samples as a function of wind speed at each station.

Noise records were typically 70 to 135 seconds long. Each time series was inspected visually and edited if small seismic events or recording errors were found or discarded if the record was clearly dominated by digitizer noise. Only those time series with a duration of 40 seconds or more and for which wind speed was recorded were used. In the end we selected close to 2,000 noise records from the U.S. stations and about 1,000 from the Soviet Union.

3.2. Time series analysis

We calculated power spectra using a Hann taper and a section-averaging algorithm with 10 second sections and 50 percent section overlap (e.g. Welch, 1967). The influence of monochromatic spikes —typically at 50 Hz in the U.S.S.R. and 60 Hz in the USA— and their harmonics was reduced by smoothing the spectra with a 1 Hz running median filter. A running median was chosen because it removes small extremes in the spectrum (less than 0.5 Hz in bandwidth) without affecting significantly the adjacent noise levels—unlike a running mean which smears a spike in the data thus increasing the adjacent noise levels and changing the general shape of the spectrum. We then converted all spectra to acceleration and removed the system response. Using this procedure, we computed 30 to 60 noise spectra for each component at each station in the U.S.S.R. and approximately twice as many from the U.S. data.

Figures 7 through 12 summarize the statistics of noise spectra —acceleration noise power levels in dB relative to 1 $(m/s^2)^2/Hz$ — observed under all wind conditions at each of the six stations. On each frame are plotted the frequency-by-frequency mean of all available spectra for the corresponding channel, as well as an individual "high-noise" and

"low-noise" spectrum extracted from this population. The latter were simply selected as the spectra with the highest and lowest power integrated over the 1-80 Hz band.

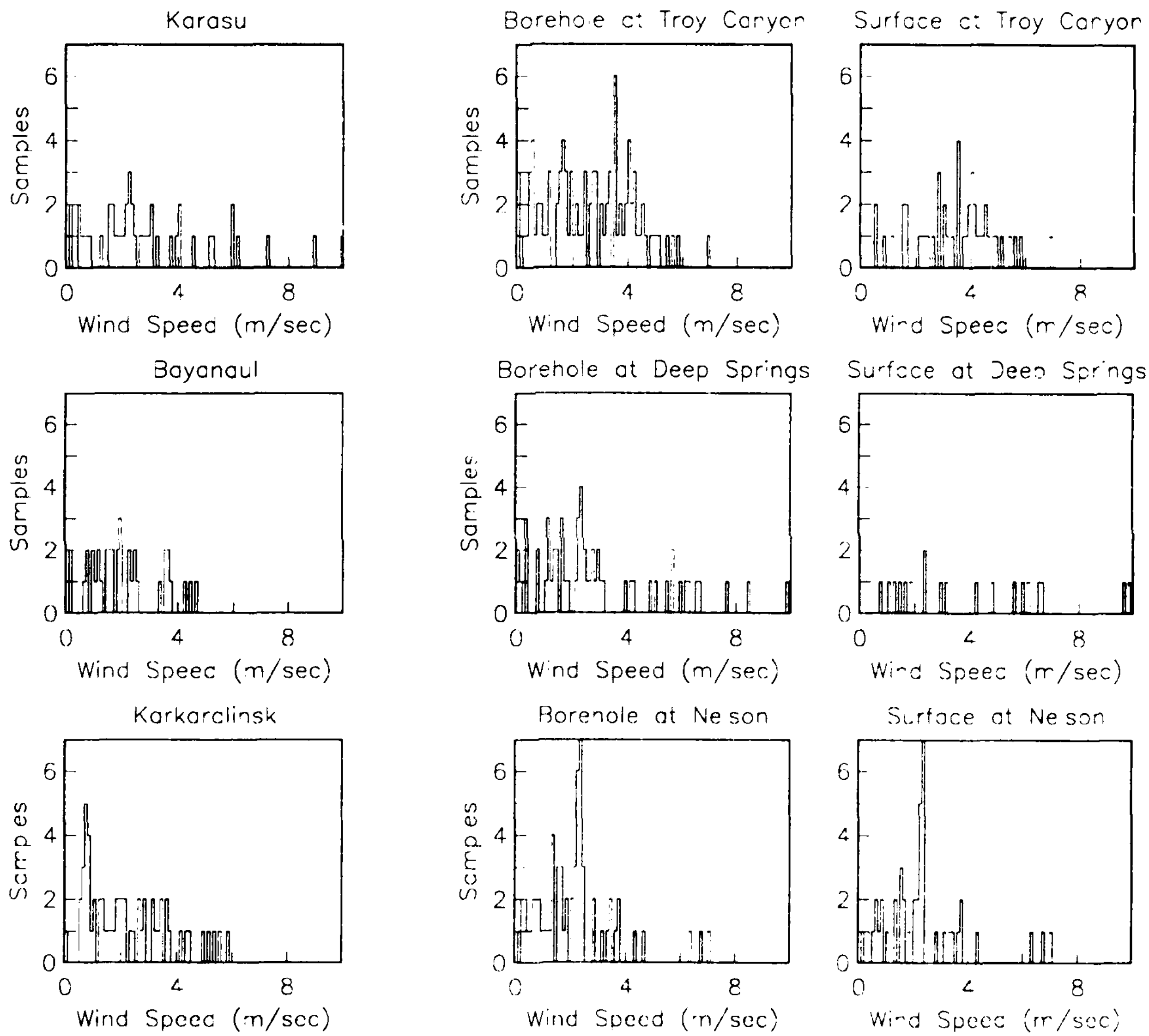

Figure 6. Histograms of number of noise data vs wind speed.

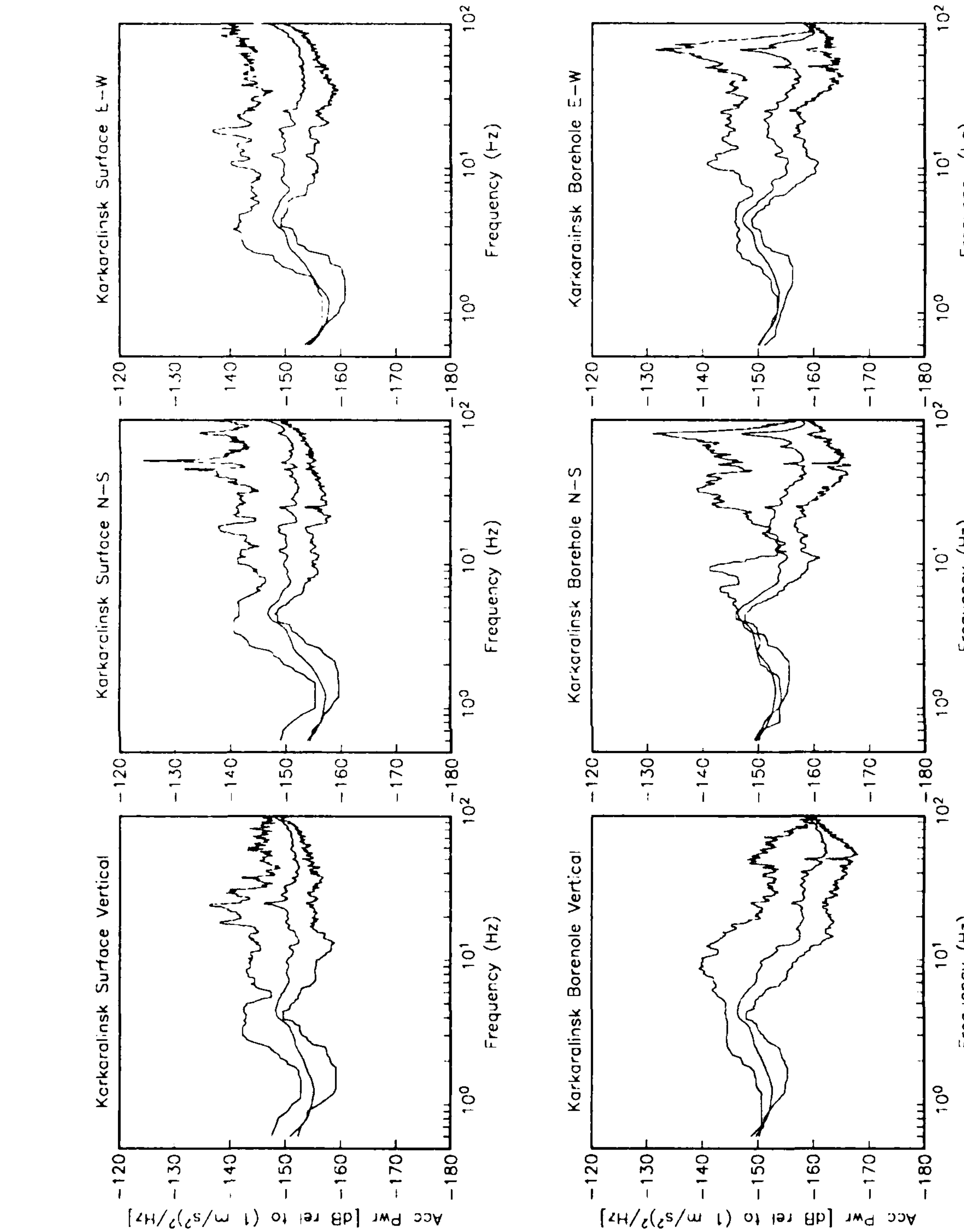

Figure 7. Mean, maximum, and minimum noise levels at Karkaralinsk, U.S.S.R.

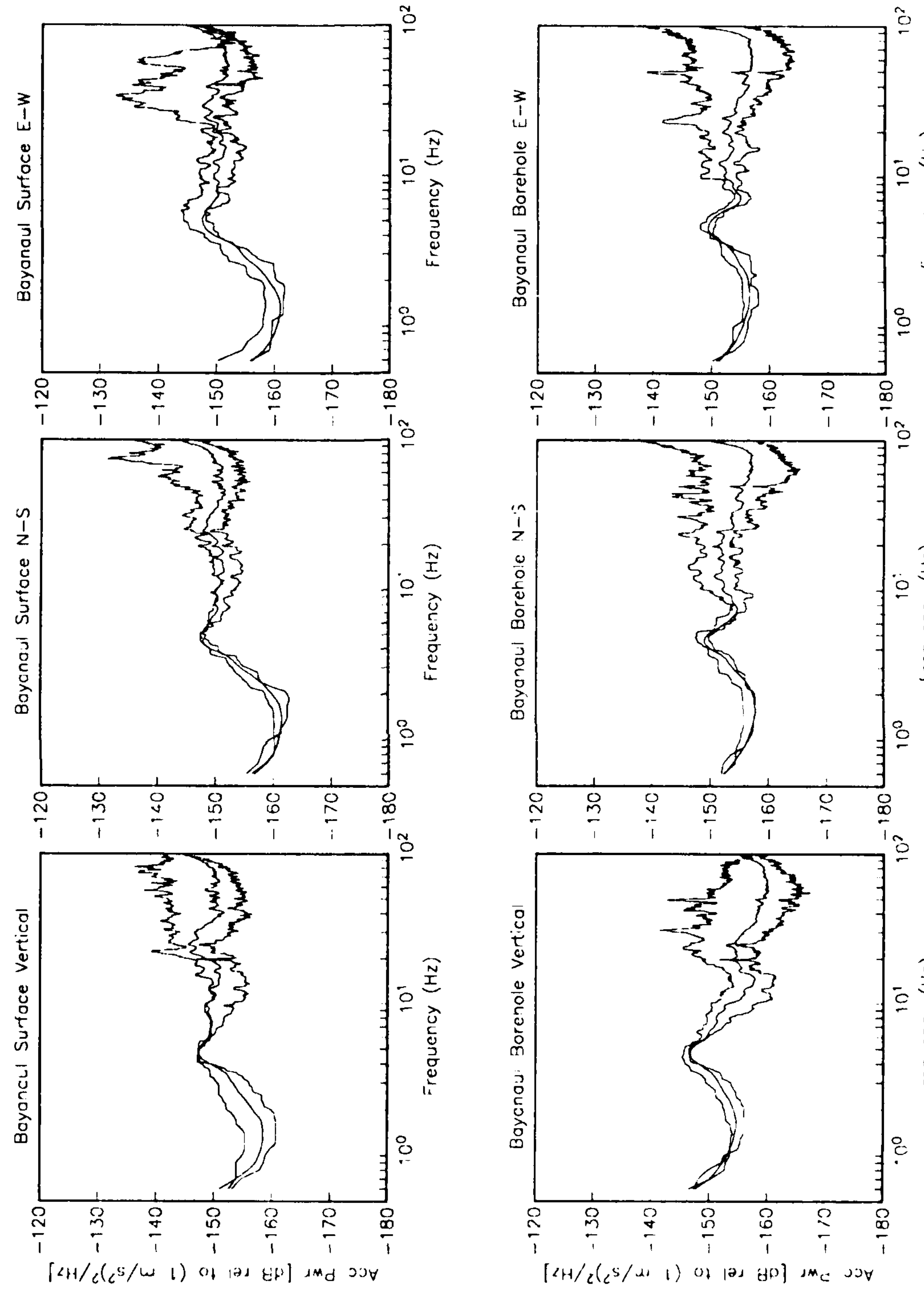

Figure 8. Mean, maximum, and minimum noise levels at Bayanaul, U.S.S.R.

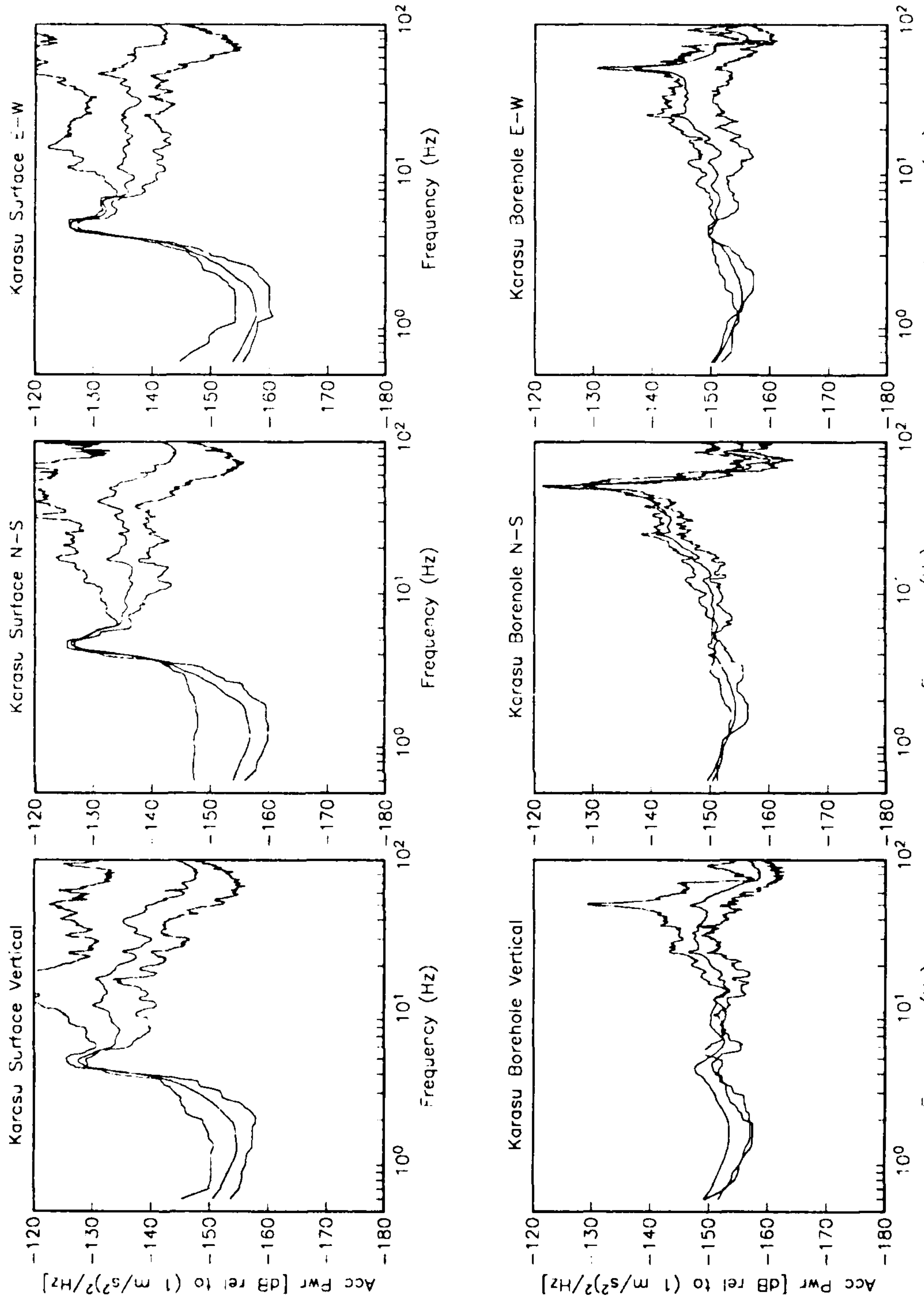

Figure 9. Mean, maximum, and minimum noise levels at Karasu, U.S.S.R.

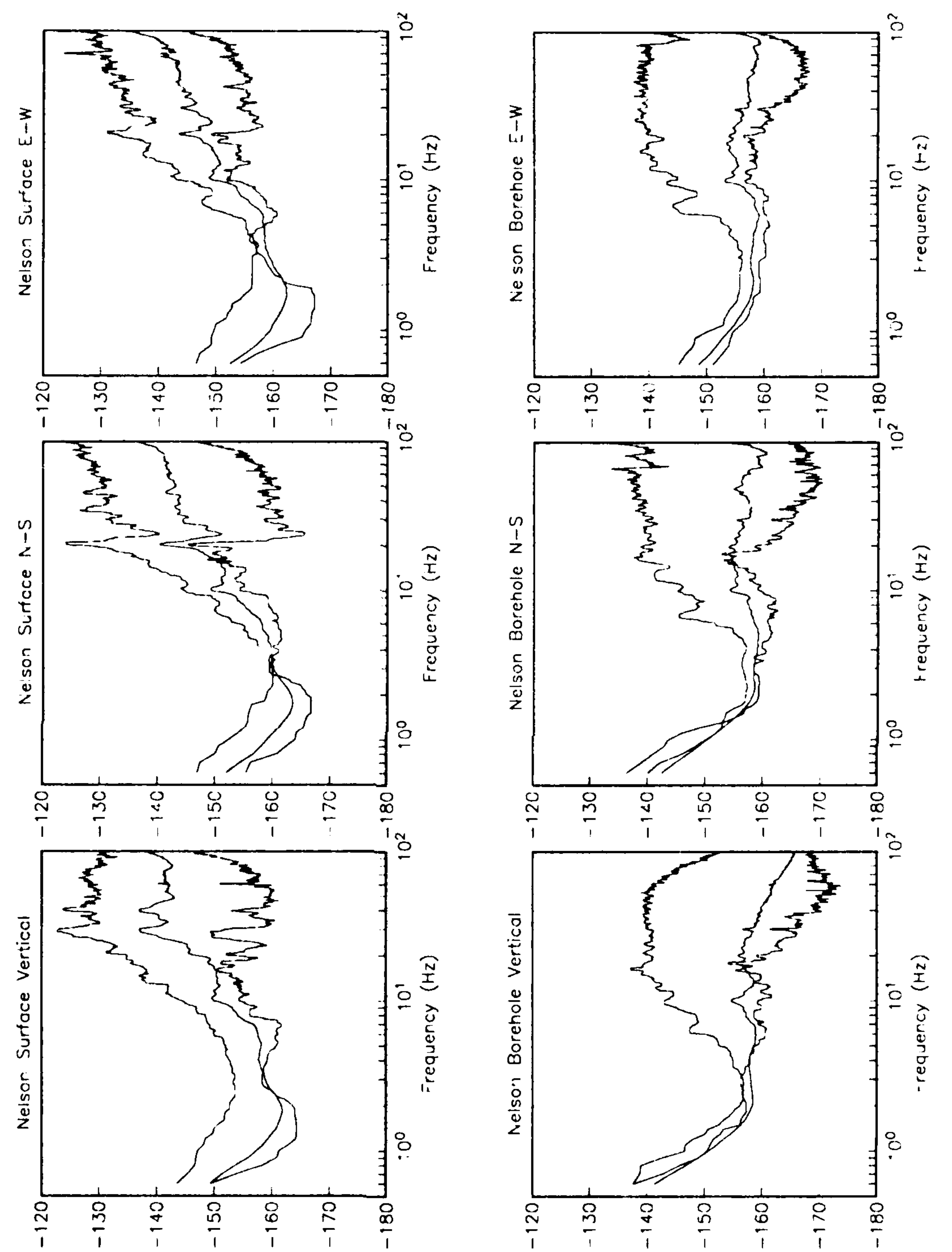

Figure 10. Mean, maximum, and minimum noise levels at Nelson, Nevada.

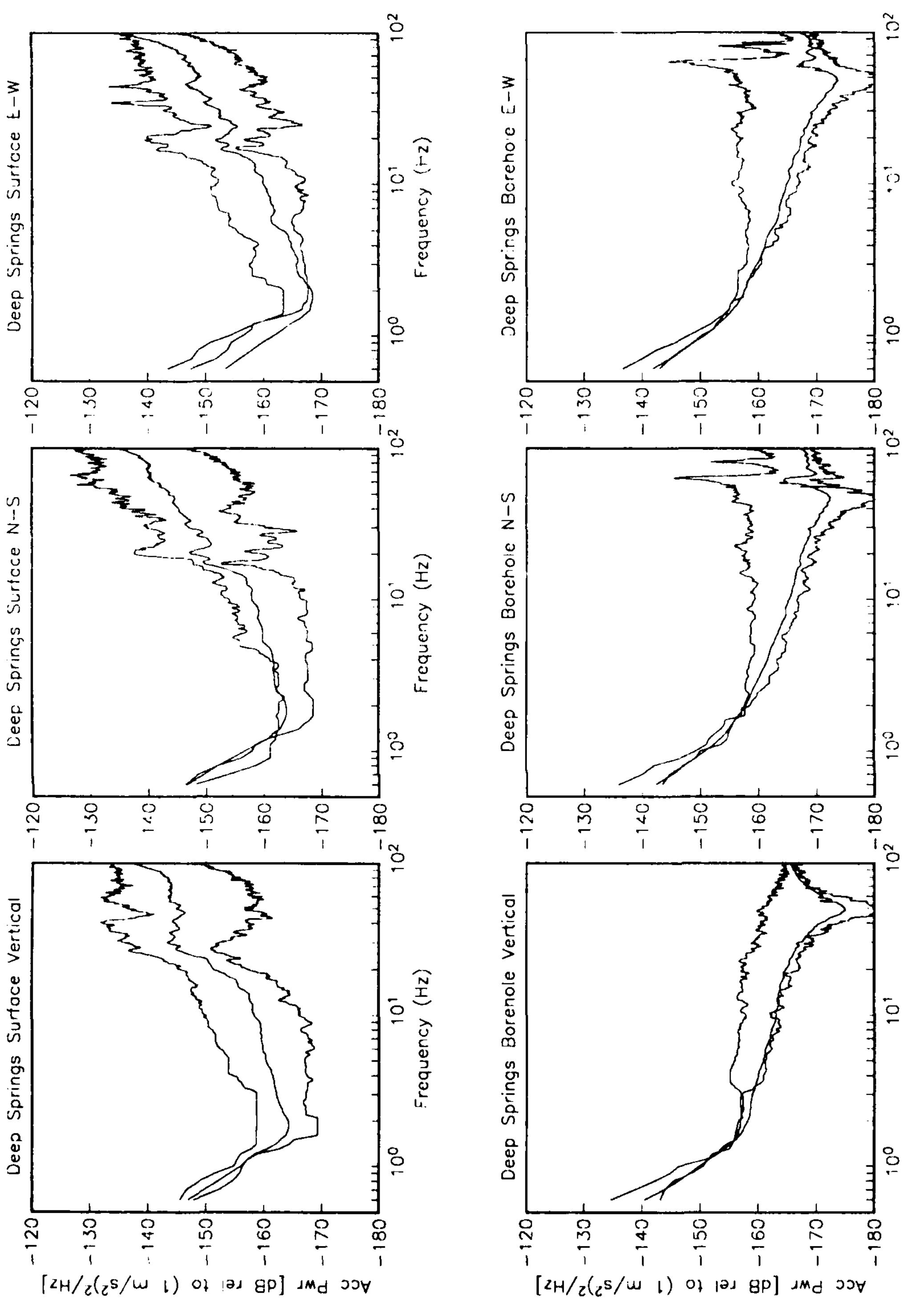

Figure 11. Mean, maximum, and minimum noise levels at Deep Springs, California.

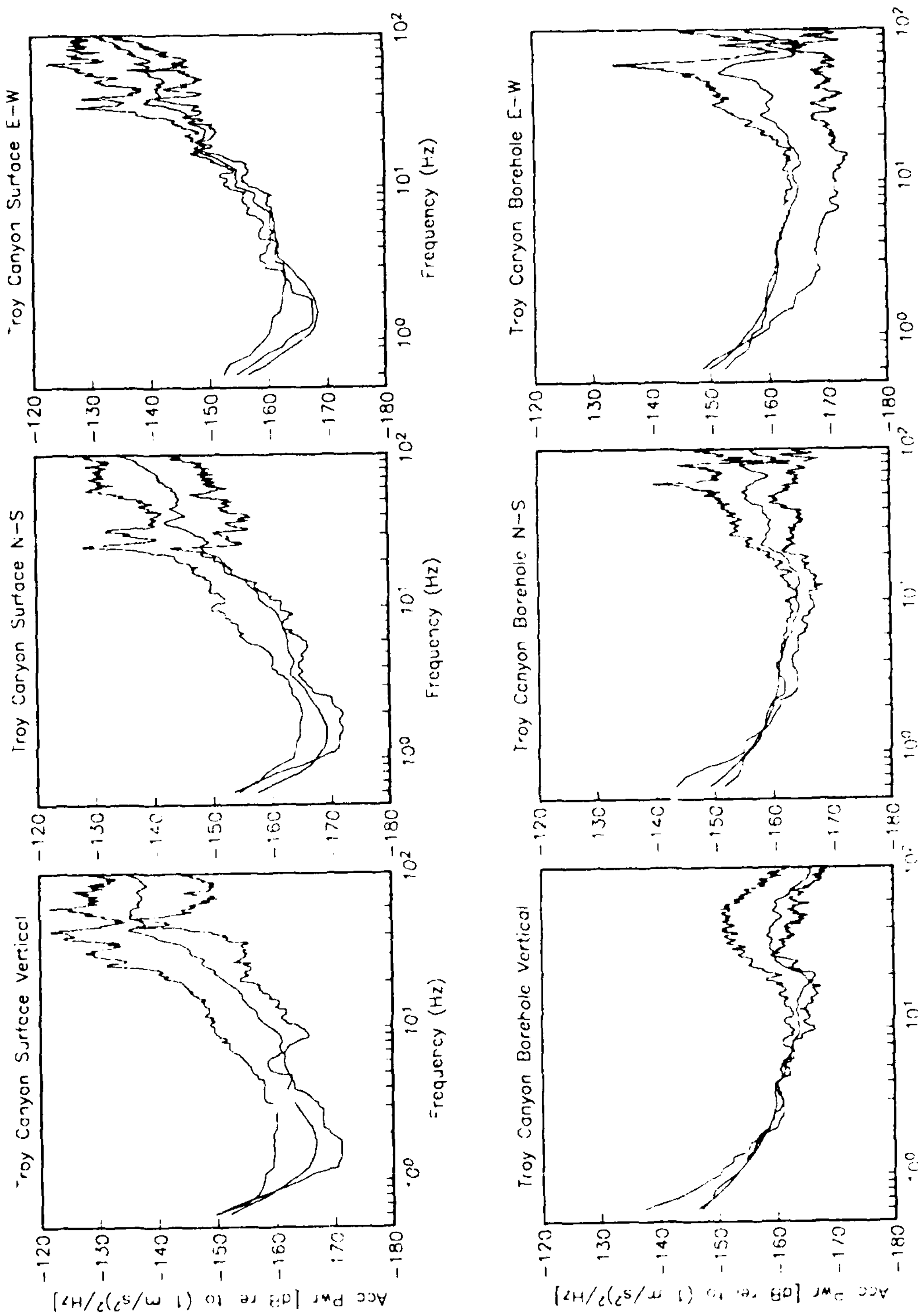

Figure 12. Mean, maximum, and minimum noise levels at Troy Canyon, Nevada.

3.3. Wind conditions analysis

The large number of spectra calculated allowed us to examine in greater detail the noise dependence on wind speed, for both surface and borehole installations. The results are summarized in Figures 13 through 18, which show contour plots of noise power versus wind speed and frequency (each station experienced a different range of wind speeds over the duration of the deployment, see Figure 6). These contour plots were obtained by averaging spectra in wind speed "bins" of 0.1 m/s and spline–interpolating the results in frequency. The grids were produced in log-frequency vs linear-wind speed and smoothed using a two-dimensional running median (over a 5 grid cell radius). Figures 13 through 18 show considerable variability in the noise character among the various sites, although general patterns do emerge as discussed below.

4. Results

We shall first give a brief description of the noise character of each station (referring to figures 7 through 18) and then compare characteristics common to all stations.

4.1. Station noise characteristics

For the U.S.S.R. stations, the noise characteristics at Karkaralinsk (Figures 7 and 13) and at Bayanaul (Figures 8 and 14) are very similar. The mean surface noise levels at these stations remain typically within a few dB of the -150 dB level across the spectrum. The mean borehole noise levels fluctuate about an average level of -153 dB below 10 Hz, and drop by approximately 3 dB above 10 Hz.

At both stations, borehole noise levels increase very little (< 2 dB) with a 5 m/sec increase in wind speed, whereas surface noise spectra show a 5 dB increase over the same range of wind speed. Unfortunately, our data cover a limited range of wind speeds at these stations (6 m/s at Karkaralinsk and 5 m/s at Bayanaul). Most of the increase in noise level with wind speed occurs at frequencies above 30 Hz for all channels.

At Karasu, the surface noise is dominated by a site resonance discussed by Berger *et al.* (1988), which results in a 30 dB increase near 4 Hz (Figures 9 and 15). Borehole noise, on the other hand, is only a few dB higher than at the other two Soviet stations and exhibits a similar character. Wind speeds of up to 10 m/sec were recorded at Karasu. Borehole noise appears to be even less sensitive, and surface noise more sensitive to wind speed than at the other two Soviet stations.

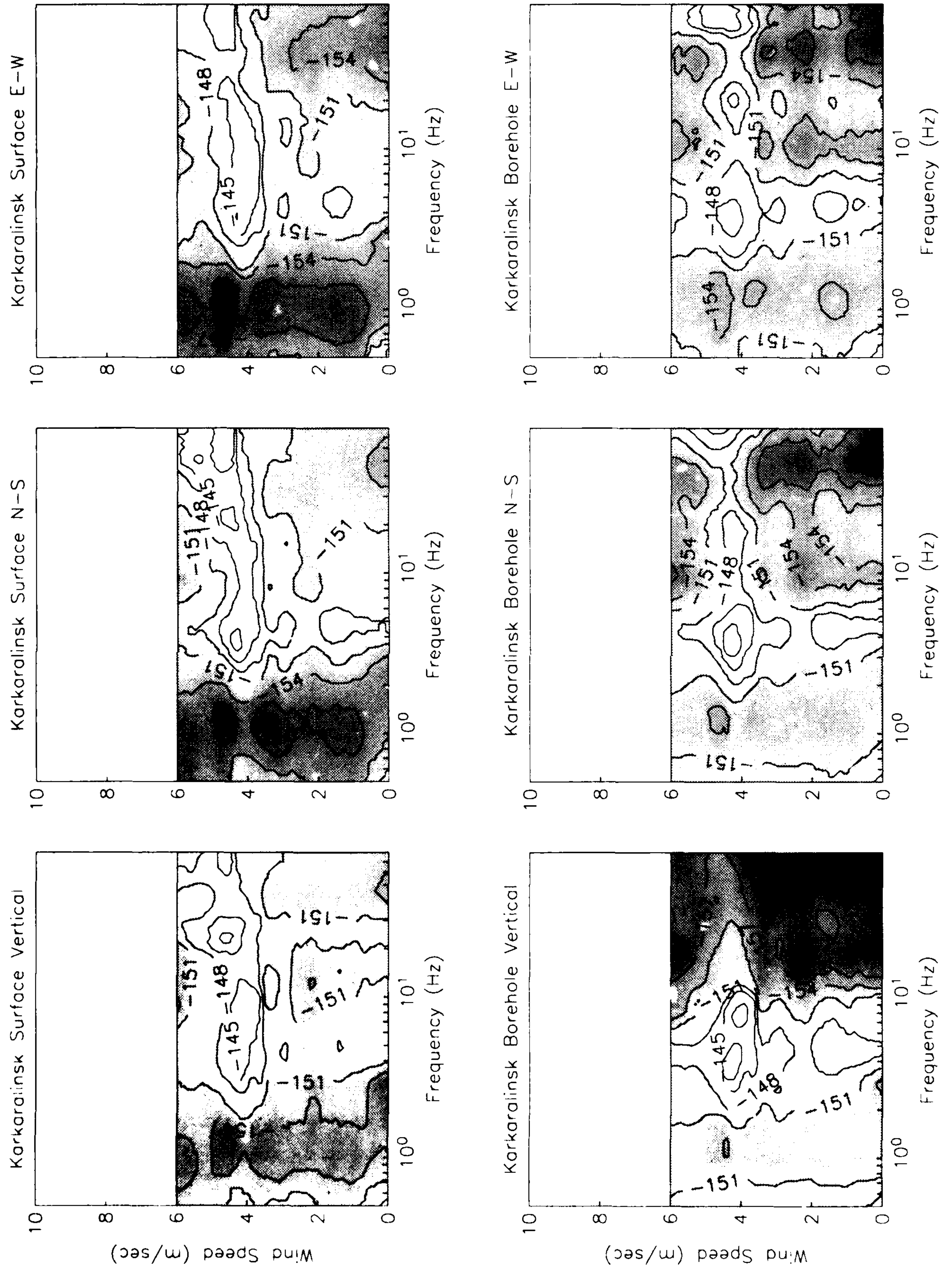

Figure 13. **Contour maps (3 dB interval) of noise levels at Karkaralinsk vs frequency and wind speed**

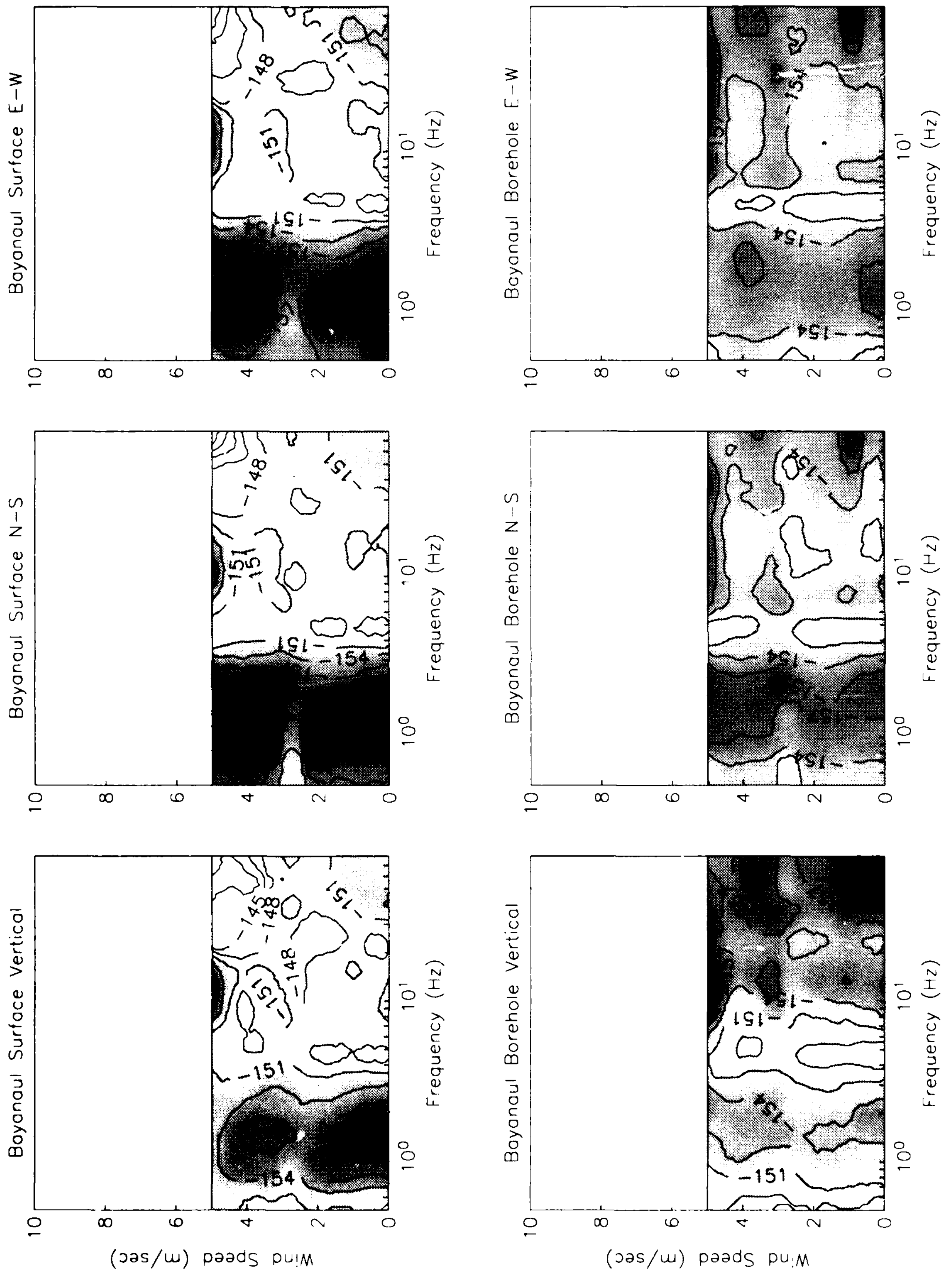

Figure 14. Contour maps (3 dB interval) of noise levels at Bayanaul vs frequency and wind speed

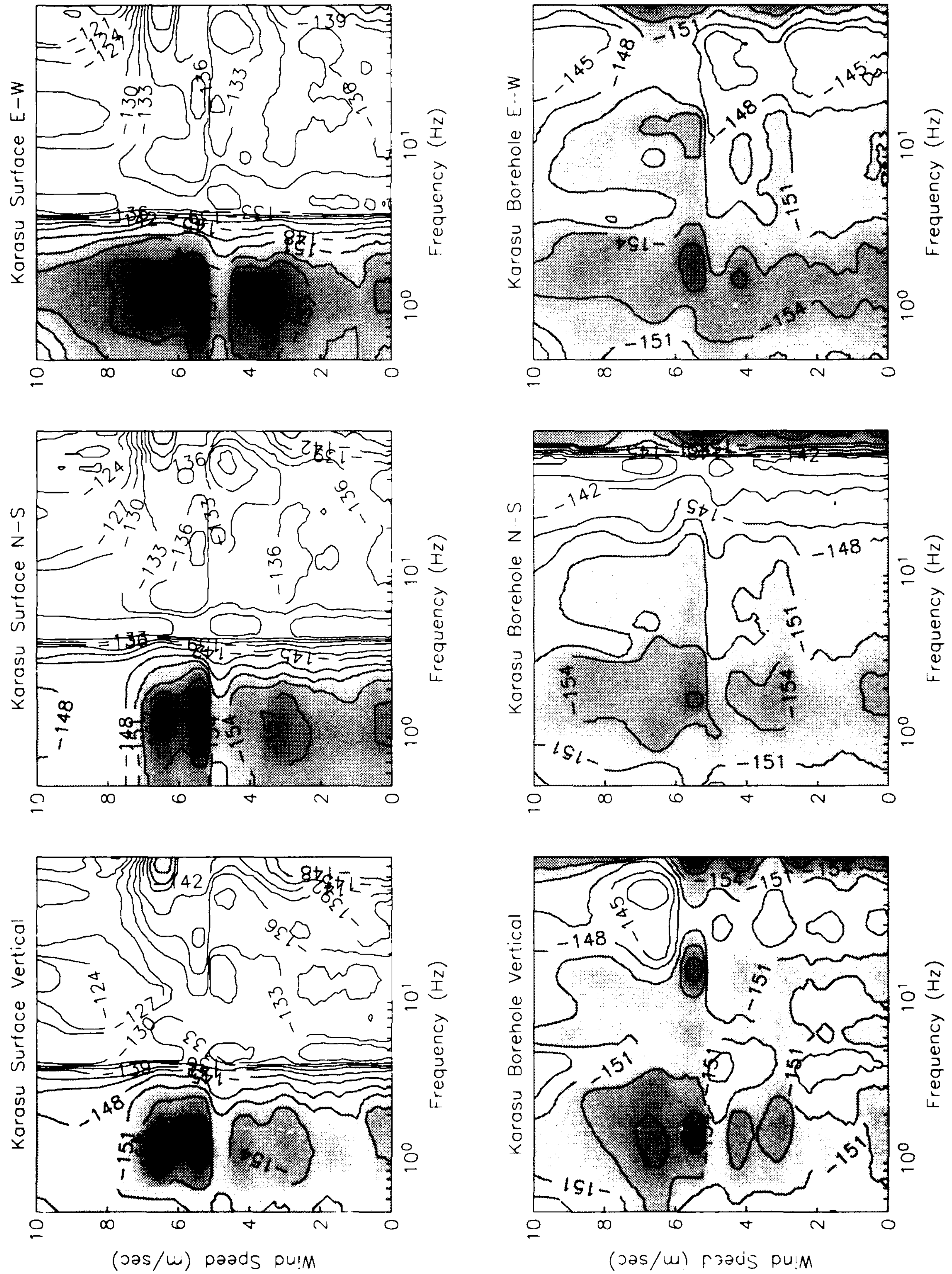

Figure 15. Contour maps (3 dB interval) of noise levels at Karasu vs frequency and wind speed

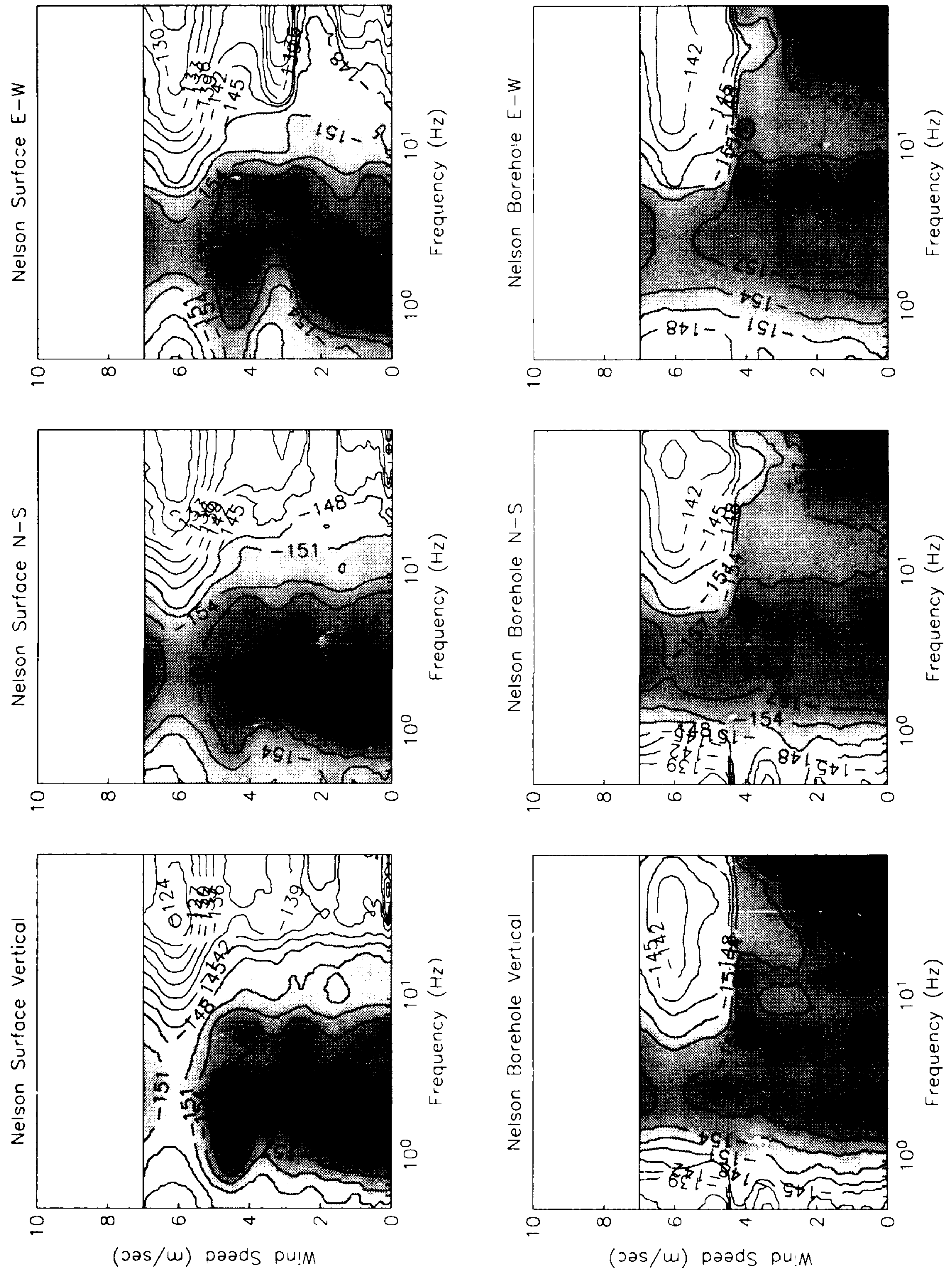

Figure 16. Contour maps (3 dB interval) of noise levels at Nelson vs frequency and wind speed

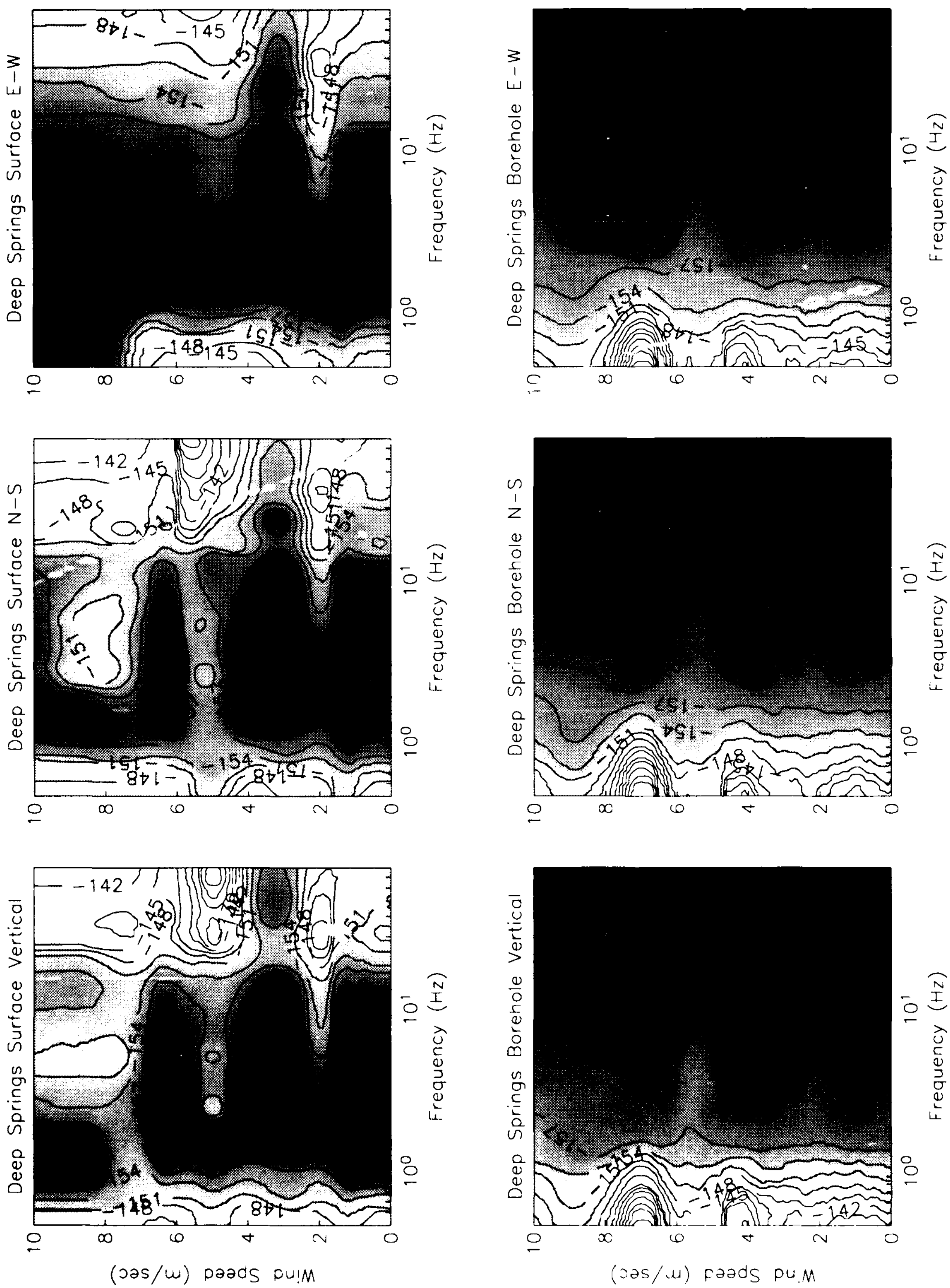

Figure 17. Contour maps (3 dB interval) of noise levels at Deep Springs vs frequency and wind speed

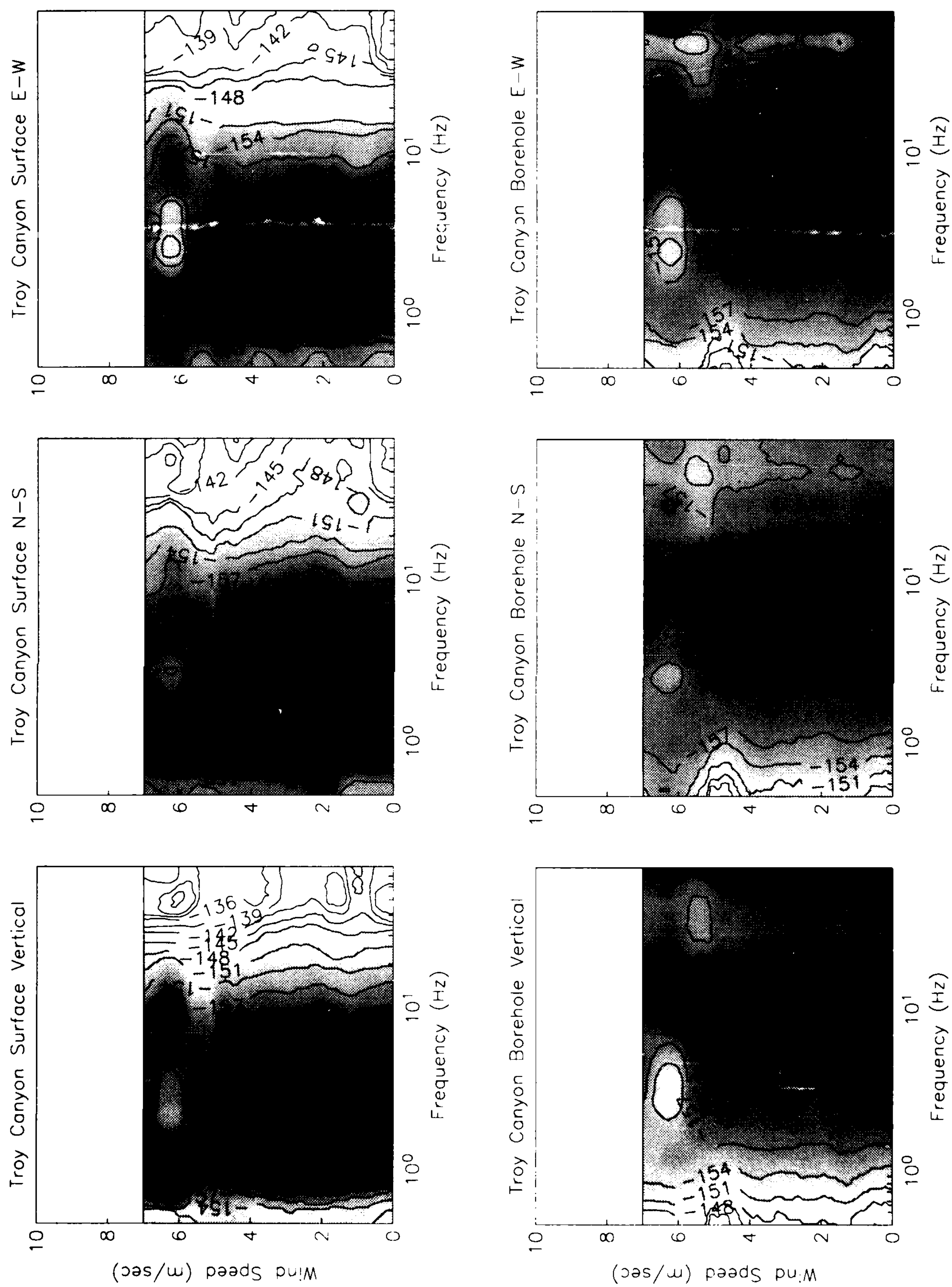

Figure 18. Contour maps (3 dB interval) of noise levels at Troy Canyon vs frequency and wind speed

Noise characteristics at U.S. stations were more varied than at the Soviet stations (Figures 10-12 and 16-18). Surface noise levels range from -168 dB at Troy Canyon and Deep Springs (at low frequency) to -160 dB at Nelson on quiet days, and rise to -145 dB (Deep Springs) or even -127 dB (Nelson) on noisy days. Borehole noise levels are typically -155 to -158 dB at low frequencies and are flat or decreasing with frequency, dropping to as low as -165 dB at high frequency , with some exceptions at Nelson. The borehole and surface noise levels at Deep Springs are among the lowest observed at any of the stations; in fact the borehole noise levels appear to be close to instrument noise.

All the U.S. sites show surface noise levels increasing with wind speed. Wind speeds of up to 7 m/sec were recorded at Troy Canyon and Nelson. At Deep Springs, some data were available with wind speeds up to 10 m/sec, however the surface channels were often set at too low a gain, thereby recording only digitizer noise and resulting in an irregular contour plot on Figure 17. The surface noise at U.S. stations increases by up to 6 dB across the spectrum over the range 0-7 m/sec. Over the same range borehole noise levels increase only by an average of about 3 dB . Nelson shows the highest sensitivity of noise on wind speed of any of the stations discussed in this paper (20 dB across the 7 m/sec range in wind speed at frequencies above 20 Hz), and is the only station in which the increase in borehole noise level with wind speed approaches that of the surface channels. We believe that the broad spectral peaks seen at high frequencies for some of the borehole sensors (e.g. 50 Hz at KSU and 60 Hz at DSP, TRC; see Figures 9, 11, 12) are artifact due to a combination of sources such as the borehole seating mechanism, and feedback electronics (note the frequencies).

4.2. Surface noise vs borehole noise

In general, borehole noise levels are significantly lower than surface noise levels, but this is mostly true for frequencies above 10 Hz.

At frequencies below 1 Hz, the spectral shape of surface noise is controlled primarily by the height of the microseismic peak, which can be measured directly at the U.S. stations from the broad-band records. On that basis, microseismic noise appears to be considerably more pronounced at U.S. stations than at the Soviet stations, which comes as no surprise since the Soviet sites are far removed from the ocean. Borehole noise spectra are likely to be contaminated by instrument noise at these frequencies (see Figure 5). The contamination is amplified when we correct the spectra for the system response, which is

probably the reason why the borehole noise appears to be higher than surface noise near 0.5 Hz at U.S. stations.

Between 1 and 3 Hz, higher noise levels are often observed in the borehole than at the surface. This occurs in cases were surface noise levels are lower than the theoretical noise curve of the borehole sensors (Figure 5). In such cases, the lower limit of ground noise cannot be resolved on borehole recordings and the mean level recorded is again biased by the seismometer noise. Therefore, comparisons of surface and borehole data in this frequency band do not necessarily reflect variation of ground noise levels.

At frequencies between 3 and 10 Hz, the surface and borehole noise levels are comparable. In general, below 10 Hz, both surface and borehole noise levels show very weak dependence on wind speed.

The dependence of noise level on wind speed is generally stronger at higher frequencies (above 10 Hz). In the 10-80 Hz band, surface noise levels are considerably higher than borehole levels (by 3 to 15 dB) and are more sensitive to change in wind speed. The largest difference between borehole and surface noise is usually found above 20 Hz. This is roughly the frequency at which the 100 m depth of the borehole exceeds the wavelength of surface waves. This is also a depth above which high-frequency body waves are rapidly attenuated (e.g. Malin, 1989).

4.3. *Surface noise vs wind speed*

No significant correlation between surface noise and wind speed is observed for wind speeds below 4 m/s; however, for stronger wind conditions, we find a noticeable increase of 1 to 2 dB for each increment of wind speed of 1 m/s. Wind speed appears to be a noise controlling factor above this 4 m/s threshold. This is reflected in the abrupt change in dominant contour directions on Figures 13-18 at or near the threshold. In general, the highest surface noise levels are found at high frequency for the highest observed wind speed and the lowest noise levels are observed near 1 Hz at low wind speeds.

4.4. *Borehole noise vs wind speed*

At all sites except Nelson, we find that noise in the borehole was essentially unaffected by wind speed over the range of observations; furthermore, this weak dependence was confined to speeds greater than 4 to 5 m/sec. The anomalous beahvior at Nelson is not understood.

In general, the lowest noise levels in the boreholes were observed at low wind and high frequency. The highest noise levels overall occured at frequencies below 1 Hz, and are

thought to be related to the microseism peak. In the 3 to 80 Hz band, the highest noise levels tended to be at frequencies below 10 Hz at high wind.

5. Discussion

5.1. Comparison of U.S. and U.S.S.R. stations

At frequencies greater than 10 Hz, surface noise levels at the three U.S. stations are approximately 5 to 10 dB higher than at Karkaralinsk and Bayanaul. At lower frequencies, the U.S. sites are quieter. Surface noise levels observed at Karasu are the highest in our data set, due to a local site effect. In general, surface noise at the U.S. sites increases faster with frequency and is more sensitive to wind speed than at the Kazakh sites. The contour plots shown on Figures 13-18 are also more complicated for U.S. stations than for U.S.S.R. stations. We suspect that this is a result of differences in the vault designs.

Borehole noise spectra computed for the Soviet stations also are somewhat different from those observed at the American sites. We can distinguish three main regimes:

- Below 1 Hz, the U.S. spectra rise significantly, whereas the U.S.S.R. spectra remain rather flat. This is consistent with the independent observation made on broad-band recordings that the microseismic peak is much stronger in U.S. than in Kazakhstan. Data in the frequency band below .2 Hz are unavailable at the three stations around the Kazakh test site, however comparison of broad band noise at the three Nevada stations with the noise spectrum presented by Given (1990) for the four IRIS stations currently operating in the Soviet Union indicates that the microseismic peaks in those regions of the USSR are several dB lower than in southern Nevada.
- In the 1-3 Hz band, the low borehole noise levels are uncertain, however the high noise samples in the U.S.S.R. are noisier than those in the U.S.
- In the 3-10 Hz band, all spectra are more or less flat, but the levels recorded in U.S. are lower than those recorded in Kazakhstan.
- In the 10-80 Hz band, Kazakh spectra typically drop with increasing frequency. A similar behavior —flat or decreasing spectrum— is observed at Deep Springs, but some spectra computed for Troy Canyon and Nelson increase through this range. These trends are weak, however, and there appears to be little variation in overall spectral levels from site to site at frequencies in excess of 30 Hz. Although there were differences in the shape of the borehole noise spectrum between data recorded in the U.S. and the U.S.S.R., the average noise level in the 10-80 Hz band was similar in both deployments.

In the 1-20 Hz band, the surface noise levels observed at all stations except Karasu are not systematically different from those recorded at NORESS (e.g. Suteau-Henson and Bache, 1988). The NORESS noise spectra calculated by Hedlin *et al.* (1989) show a strong peak at frequencies below 1 Hz, comparable to our observations for U.S. sites. Where borehole noise is concerned, our results in the 1 to 20 Hz band are comparable to those obtained for the Regional Seismic Test Network stations (Rodgers *et al.*, 1987); at Deep Springs, noise levels in the same band are within a few dB of the low levels reported by Li *et al.* (1984) for Lajitas, Texas (see Berger *et al.*, 1988, Figure 11). The low noise levels observed at the stations described in this study can be attributed at least in part to the fact that they are all located in remote areas, thus minimizing cultural noise.

We suspect that the high frequency surface noise levels at the Soviet stations were lower than those of the U.S. stations at least partly as a result of differences in the vault designs. This conclusion is supported by the fact that a similar relationship was not observed in the borehole noise levels. In particular, the smaller surface vaults in the U.S. were exposed to environmental noise sources to a greater extent than the larger subterranean Soviet vaults, in which surface instruments were actually placed on a pier decoupled from the vault itself (Berger et al., 1988).

5.2. *Comparison of Surface and Borehole Emplacements*

In the 3 to 80 Hz band, borehole noise appears to be lower than surface noise at all stations. We have plotted on Figure 19 the ratio of surface to borehole noise levels on the vertical components at Bayanaul (curve A) and Troy Canyon (curve B) under low wind conditions (less than 1 m/sec). In the 10 to 80 Hz band, curve A, typical of all three components at Bayanaul and Karkaralinsk, indicates that the surface noise is 4 to 11 dB higher than the borehole noise. Curve B, which is typical for all components at U.S. sites, shows a ratio ranging from 3 to 20 dB in the 10 to 80 Hz band. At all sites but Nelson, this ratio increases with wind speed. In this frequency range, the surface to borehole noise ratio typically increases suddenly at 5 m/sec, by 3 dB for Soviet stations and 6 dB for U.S. stations. Thus, borehole emplacement of seismometers greatly improves data quality at frequencies above 10 Hz. Between 3 and 10 Hz, borehole and surface noise levels may not differ nearly as much.

In a study at three mines in Sweden, Bath (1973) reported that the 8 to 33 Hz noise levels observed at a depth of 100 m were reduced in amplitude to about 13 % of that observed at the surface, a difference of about 18 dB. This is similar to our results for the noisier of the U.S. stations in the 10 to 80 Hz band. The U.S.S.R. stations experienced

less noise reduction at these frequencies, however. This suggests that vault design improvements alone may help reduce surface noise levels at higher frequencies (greater than 10 Hz) by up to 10 dB. At lower frequency (3 to 10 Hz) the superior vault construction in the Soviet Union apparently did not greatly affect this noise ratio.

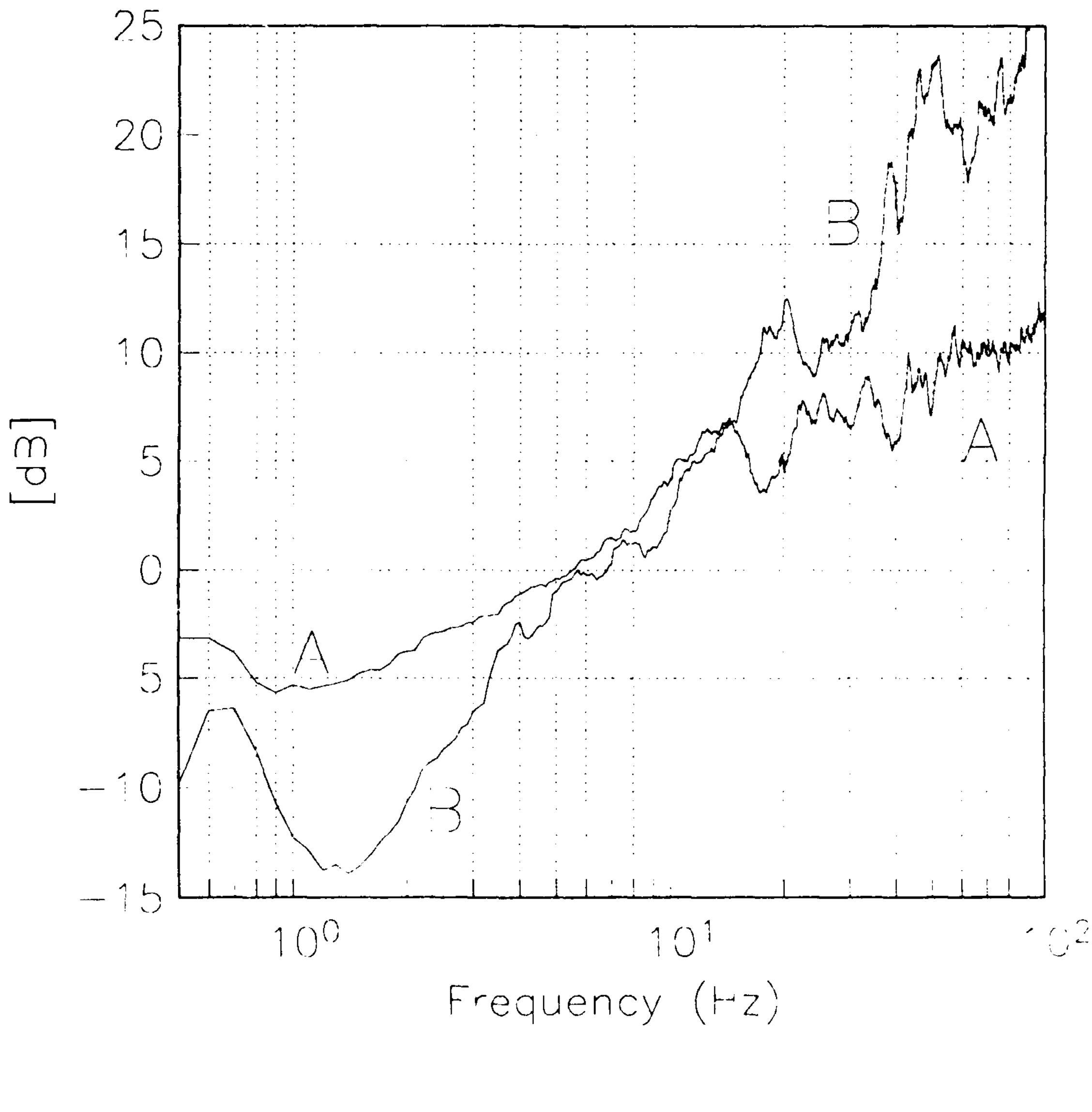

Figure 19. Surface to borehole noise ratio at: A) Bayanaul and B) Troy Canyon.

6. Conclusions

From an analysis of several hundred surface and borehole noise samples collected in 1987 at three sites in Kazakhstan and 2,000 samples collected in 1988-89 at three sites in the western United States, we conclude that:

1. In general, noise levels in the 100 m deep boreholes were affected by wind conditions to a much smaller degree than were the surface emplacements.
2. Wind did not become a noticeable source of noise at the surface emplacements until a minimum wind speed was reached (typically 4 to 5 m/sec).
3. Between 3 and 10 Hz, surface and borehole noise levels were comparable, but downhole noise levels were strongly reduced at higher frequencies.
4. Between 3 and 10 Hz, surface and borehole emplacements in the western U.S. were generally quieter than those in Kazakhstan.
5. At high frequencies, in the 10-80 Hz band, surface installations in the western U.S. were considerably noisier than surface installations in Kazakhstan, but borehole installations in both regions yielded comparable noise levels. We suspect that the difference in surface vault quality between the two sets of stations is a significant factor. In this frequency band, borehole noise was lower than surface noise at all stations.

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